The Extragalactic Neutrino Background Radiations From Blazars and Cosmic Rays

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Abstract

Blazar emission of gamma rays and cosmic ray production of gamma rays in gas-rich clusters have been proposed recently as alternative sources of the high energy extragalactic diffuse gamma ray background radiation. We show that these sources also produce a very different high energy extragalactic diffuse neutrino background radiation. This neutrino background may be detected by the new generation of large neutrino telescopes under construction and may be used to trace the origin of the extragalactic gamma radiation.

In addition to the galactic diffuse gamma radiation, which varies strongly with direction and can be explained by cosmic ray interactions in the galactic interstellar medium [1], there appears to be a diffuse extragalactic gamma radiation which is isotropic at least on a coarse scale [2]. Its existence has been confirmed recently by analyses of observations with the Energetic Gamma Ray Experiment Telescope (EGRET) on board the Compton Gamma Ray Observatory (CGRO) [3–5]. Various unresolved extragalactic discrete and diffuse sources of gamma rays had been suggested in the past to explain its origin, but all of them have been later questioned by observations [6]. Recently, however, attention has focused on two alternative sources of the extragalactic diffuse gamma ray background radiation (GBR): The detection of some active galactic nuclei (AGN) by EGRET in high energy gamma rays, all belonging to the blazar type [7], has led to the suggestion that blazar emission has produced the extragalactic diffuse GBR [8]. On the other hand, the discovery of very large mass of gas in intergalactic space within groups and clusters of galaxies with the ROSAT and EINOBS X-ray telescopes [9] has led to the alternative suggestion that cosmic ray interactions in groups and clusters produced the extragalactic diffuse GBR [10]. In this paper we show that these two alternative sources should have also produced a diffuse extragalactic high energy neutrino background radiation (NBR). These backgrounds are very different for the two sources. They may be detected by the new generation of large neutrino telescopes under construction and may help to trace the origin of the extragalactic diffuse GBR.

When it was first suggested that the diffuse extragalactic GBR is the sum of gamma ray emission from unresolved AGN [11] only the relatively nearby quasar 3C 273 had been seen in high energy gamma rays [12] ($E > 100 \ MeV$). Since the launch of CGRO, 33 AGN were detected with EGRET in high energy gamma rays [7], all of which seem to belong to the blazar class. Many more AGN including blazars, which are both bright and relatively close and which were within the EGRET field of view, have not been detected in high energy gamma rays, indicating that not all of these objects are so luminous in gamma rays, or their emission is highly beamed or has a low duty cycle. The beaming hypothesis is further supported by other features of the sources such as superluminal velocity, beamed radio emission, and a power-law gamma ray spectrum (with a power index between 1.4 and 3.0, with values between 1.8 and 2 being most common). Although it is difficult to see how the observed isotropic GBR can be produced by the highly beamed and time variable emission from blazars, many of which have a much harder spectrum than that of the GBR, some authors have actually shown that blazars with a plausible evolution function could have produced the observed extragalactic GBR [8]. If blazars produce their high energy beamed gamma rays via inverse Compton scattering or via electron-positron annihilation in

flight then blazars are not significant cosmic sources of high energy neutrinos. However, if blazars accelerate high energy cosmic ray nuclei that collide with matter or radiation and produce neutral pions which decay into the observed high energy gamma rays, then they also produce charged pions and kaons which decay into high energy neutrinos [13]. Since the blazar luminosities in high energy gamma rays are much larger than their luminosities in lower energy photons, the gamma ray blazars cannot be "hidden sources" of high energy neutrinos [14]. The summed emission of such blazars produces both a diffuse extragalactic GBR and a diffuse extragalactic NBR which are closely related.

The second explanation of the extragalactic diffuse GBR was motivated by the recent discoveries of large quantities of gas in intergalactic space within groups and clusters of galaxies [9]. Most of the high energy gamma ray emission of our Milky Way (MW) galaxy can be explained by cosmic ray interactions with its interstellar gas [1,6]. But simple considerations show that the summed contributions of gamma ray emission from external galaxies falls short by more than an order of magnitude [15,6] in explaining the observed flux [2–5] of the GBR [16]. However, whereas the ratio of the total mass of gas to light in the MW is only [17] $M_{gas}/L_{MW} \approx 4.8 \times 10^9 M_\odot/(2.3 \pm 0.6) \times 10^{10} L_\odot \approx 0.21 \ M_\odot/L_\odot$, recent X-ray observations of groups and clusters of galaxies have shown that they contain much larger mass of intergalatic gas than their total stellar mass [9]. For instance, analyses of recent observations with the ROSAT X-ray telescope of the compact group HCG62 and the Coma cluster yielded, $M_{gas}/L_B \approx 4.4 \times 10^{11} M_\odot h^{-5/2}/2.4 \times 10^{10} h^{-2} L_\odot \approx 19 h^{-1/2} M_\odot/L_\odot$, within a distance of $0.24 h^{-1} \ Mpc$ from the center of HCG62 [18], and $M_{gas}/L_B \approx (5.45 \pm 0.98) \times 10^{13} M_\odot h^{-5/2}/1.8 \times 10^{12} h^{-2} L_\odot \approx (30 \pm 6) h^{-1/2} M_\odot/L_\odot$, within a distance of $1.5 h^{-1} \ Mpc$ from the center of the Coma cluster [19]. It was also found that these ratios are rather typical to the groups and clusters of galaxies that have been detected in X-rays and for large enough radii are independent of radius. It was further argued on theoretical grounds that these ratios are universal in groups and clusters [9] and they imply that most of the baryonic matter in the Universe, as estimated from Big-Bang Nucleosynthesis, is in intergalactic gas within groups and clusters of galaxies [10]. This has been used by Dar and Shaviv [10] to show that an average cosmic ray flux in intergalactic space within clusters and groups similar to the *average* cosmic ray flux observed in the MW [20], could have produced the extragalactic GRB by interactions with the intergalactic gas in groups and clusters [21]. Such a universal cosmic ray flux in groups and clusters should have also produced high-energy diffuse galactic and extragalactic neutrino background radiations which are closely related to the diffuse galactic and extragalactic GBR.

The main mechanism by which cosmic rays produce high energy gamma rays is by

π^0 production in inelastic collisions with gas nuclei and/or background photons followed by immediate $\pi^0 \rightarrow 2\gamma$ decay. For simplicity we will assume that the target particles are gas nuclei (the results are very similar if the production takes place on background photons). The same interactions produce charged pions, kaons and small quantities of other mesons which decay into electrons and neutrinos (e.g., $\pi \rightarrow \mu\nu_\mu$, $K \rightarrow \mu\nu_\mu$, $\mu \rightarrow e\nu_e\nu_\mu$) if their mean free path for interaction is much larger than their decay path, $\lambda_d = \gamma c\tau$, with $\gamma \equiv E/m_0 c^2$. Because of the low mean baryonic density of the galactic and intergalactic gas, $\lambda_d n_b \sigma_{in} \ll 1$, and all the secondary unstable particles produced in cosmic ray collisions decay before interacting with other gas nuclei. For a power law spectrum of cosmic ray nuclei, $dF_{CR}/dE \approx AE^{-p}$, and inclusive cross sections for meson production that obey Feynman scaling, the produced fluxes of γ-rays, ν_e's, ν_μ's and ν_τ's are all proportional at high energies to the flux of cosmic ray nuclei,

$$\frac{dF_\gamma}{dE} \propto \frac{dF_{\nu_i}}{dE} \propto \frac{dF_{CR}}{dE} \ . \tag{1}$$

In particular, if $\nu_\mu + \bar{\nu}_\mu$ production proceeds mainly via π, K and μ decays then one can use the analytical methods developed, e.g., by Dar [22] and by Lipari [23] to show that the neutrino and gamma ray fluxes produced by cosmic rays are related through

$$\frac{dF_{\nu_\mu}}{dE} \approx 0.70 \frac{dF_\gamma}{dE} \ . \tag{2}$$

Relation (2) can be verified also by detailed Monte Carlo calculations. It is valid as long as the γ's are not absorbed in the intergalactic space through the process $\gamma + \gamma \rightarrow e^+ + e^-$.

We can now use Eq. (2) to estimate the extragalactic diffuse NBR at very high energies from the observed extragalactic diffuse GBR in the GeV region [2–5], $dF_\gamma/dE \approx 2 \times 10^{-6} E^{-2.1\pm0.1} \ [cm^{-2}s^{-1}ster^{-1}GeV^{-1}]$:

The power law gamma ray spectra of the 33 blazars which were detected by EGRET, if extrapolated to TeV energies, suggest that many of them should have been easily detected with currently available TeV gamma ray telescopes [24]. To date only Markarian 421, the nearest (at redshift z=0.03) of the AGN seen by EGRET, was observed in TeV gamma rays with the Whipple Observatory gamma ray telescope [25]. This has been interpreted as being due to the absorption of TeV gamma rays from distant blazars by the extragalactic IR background radiation [26]. The spectral index of Markarian 421, which is implied by the combined EGRET and Whipple observations is $p = 2.06 \pm 0.05$. If this is the typical power index of the high energy gamma ray emission by blazars then the extragalactic diffuse GBR must have this power index below 500 GeV where gamma ray absorption in intergalactic space is negligible. This power index is consistent with the best fitted [3–5] power index

of the extragalactic diffuse GBR which has been observed so far at energies below 10 GeV. If the TeV gamma rays are produced by pion decay then the observed flux level of the extragalactic diffuse GBR implies the existence of an extragalactic diffuse NBR with a flux

$$\frac{dF_{\nu_\mu}}{dE} \sim 1.4 \times 10^{-6} E^{-2.06 \pm 0.05} \left[cm^{-2} s^{-1} ster^{-1} GeV^{-1} \right],$$
(3)

which extends at least up to energies of a few TeV. Without the knowledge of the gamma ray emission of blazars beyond 10 TeV it is not possible to predict reliably the extragalactic GBR and NBR beyond 10 TeV which are produced by blazars.

If the extragalactic diffuse GBR is produced by a universal cosmic ray flux in groups and clusters, with an average flux similar to that observed in the Milky Way, then the power index of the GBR above 10 GeV must change to 2.7, which is the power index of high energy cosmic rays below 10^4 TeV. Such a cosmic ray flux must have also produced an extragalactic diffuse NBR which extends all the way to the highest cosmic ray energies. Its flux below 10^4 TeV is given by

$$\frac{dF_{\nu_\mu}}{dE} \approx 1.4 \times 10^{-6} E^{-2.7} \left[cm^{-2} s^{-1} ster^{-1} GeV^{-1} \right].$$
(4)

Eq. (2) and the observed diffuse galactic GBR can be used also to evaluate the diffuse galactic NBR. Whereas the diffuse galactic gamma radiation depends on galactic coordinates, reflecting variations in the local intensity of cosmic rays and in the density of interstellar gas in the MW, the extragalactic diffuse gamma radiation seems to be isotropic.

At low energies both the galactic and extragalactic diffuse NBR are masked by the atmospheric neutrino background. At high energies the atmospheric neutrino flux is dominated by π and K decays since the contibution from μ decays is strongly suppressed by an additional power of E. For $E >> 1 TeV$ and zenith angles not too close to the horizon, it is given approximately by [22,23]

$$\frac{dF_{\nu_\mu}}{dE} \approx 5.3 \ sec \ \theta \ E^{-3.7} \left[cm^{-2} s^{-1} ster^{-1} GeV^{-1} \right].$$
(5)

In Fig. 1 we plotted our predictions for the atmospheric NBR at zenith angles $\theta = 0^0, \ 90^0$, the galactic NBR and the extragalactic NBR produced by blazars and by cosmic rays, respectively. As can be seen from Fig. 1, an extragalactic NBR produced by blazars dominates the atmospheric NBR already at 10 TeV while an extragalactic NBR produced by a universal cosmic ray flux in groups and clusters dominates the atmospheric NBR only at energies above $\sim 4 \times 10^3 TeV$.

In principle the extragalactic NBR can be distinguished from the galactic and atmospheric NBR because it is isotropic, while the atmospheric neutrino flux at high energies

depends on zenith angle and the galactic neutrino flux depends on galactic coordinates: The galactic NBR is non isotropic even at very high energies because it is proportional to the column density of gas in the MW as seen from the solar system ($\sim 8.5kpc$ away from the center of the MW galaxy) in different directions. The atmospheric neutrino background depends on zenith angle because the probability of very energetic pions and kaons to decay and produce neutrinos before being absorbed in the atmosphere depends on zenith angle (see Eq. (5) and Refs. [22,23]). The predicted blazar produced extragalactic NBR is detectable by the large neutrino telescopes under construction [27]. The predicted extragalactic NBR produced by cosmic ray interactions in groups and clusters is detectable only by the future generations of large (> 1 km^2) neutrino telescopes [28].

It is quite possible that we have underestimated the atmospheric neutrino background at very high energies because we have neglected the contribution from production and decay of heavy flavour mesons. At energies below 1 TeV, the inclusive cross sections for production of charm, beauty and truth in proton-proton and proton-nucleus collisions are much smaller than for normal and strange meson production. Therefore π, and K production and decay dominate there the atmospheric NBR. However, at very high energies π and K decays in the atmosphere are strongly suppressed and the production of charmed and beauty mesons which decay promptly may dominate the atmospheric meutrino flux. Unfortunately, the present experimental information on heavy flavour production and decay cannot be extrapolated reliably to very high energies where their contribution may dominate the atmospheric NBR.

Many other exotic sources that may have generated an extragalactic high energy diffuse NBR have been proposed by various authors [14]. In principle, the extragalactic NBR produced by them can be distinguished from the NBR produced by the above conventional sources, by their flux levels, their spectra, and their typical spatial and temporal variabilities. **Acknowledgement**: We thank J.N. Bahcall for proposing to us to calculate the

extragalactic NBR produced by cosmic ray interactions in intergalactic space within clusters and groups of galaxies.

References and Footnotes

REFERENCES

[1] See for instance D.L. Bertsch et al., Astrophys. J. **416**, 587 (1993) and references therein.

[2] C.E. Fichtel *et al.*, Astrophys. J. **217**, L9 (1977); C.E. Fichtel, G.A. Simpson and D.J. Thompson, Astrophys. J. **222**, 833 (1978); D.J. Thompson and C.E. Fichtel, Astron. and Astrophys. **109**, 352 (1982).

[3] J.L. Osborne *et al.*, J. Phys. G. **20**, 1089 (1994).

[4] S.D. Hunter et al., Astrophys. J. 1995 (in press).

[5] S.W. Digel et al., Astrophys. J. 1995 (in press).

[6] See, for instance, P.V. Ramana Murthy and A. W. Wolfendale, "Gamma Ray Astronomy", Cambridge University Press 1993 and references therein.

[7] C. Von Montigny, *et al.*, Astrophys. J. 1995 (in press), see also S.D. Hunter, Nucl. Phys. B (Proc. Suppl.) **38**, 447 (1995).

[8] C.D. Dermer and R. Schlickeiser, Science **257**, 1642 (1992); P. Padovani *et al.*, Mon. Not. Roy. Astron. Soc. **260**, L21; F.W. Stecker, M.H. Salamon, and M.A. Malkan, Astrophys. J. **410**, L71 (1993). M.H. Salamon and F.W. Stecker, Astrophys. J. **430**, L21 (1994).

[9] L.P. David *et al.*, Astrophys. J. **356**, 32 (1990); A. Edge et al., Mont. Not. Roy. Astr. Soc. **252**, 428 (1992); U.G. Briel *et al.*, Astr. and Astrophys. **259**, L31 (1992); T.J. Ponman and D. Bertram, Nature **363** 51 (1993); S.D.M. White *et al.*, Nature **366**, 429 (1993); H. Bohringer *et al.*, Nature **368**, 828 (1994); D.A. White and A.C. Fabian, Mon. Not. Roy. Astr. Soc. **273**, 72 (1995); D.A. Buote and C.R. Canizares, Astrophys. J. (submitted); and references therein.

[10] A. Dar and N.J. Shaviv, Astro-ph (Submitted to Phys. Rev. Lett).

[11] See e.g., A.W. Strong *et al.*, J. Phys. A **9**, 1553 (1976); G.F. Bignami et al., Astrophys. J. **232**, 649 (1979); Ref. 6 and references therein.

[12] B.N. Swanenburg *et al.*, Nature **275**, 298, (1978); W. Hermsen *et al.*, 17th ICRC, **1**, 230; 1981.

[13] For a general discussion of high energy neutrino production by cosmic accelerators see for instance V.S. Berezinskii et al., "Astrophysics of Cosmic Rays" (North Holland

1990).

[14] For a recent review of high energy neutrino production by AGN see for instance V.S. Berezinsky, Nucl. Phys. B (Proc. Suppl.) **38**, 363 (1995) and references therein.

[15] See for instance A.W. Strong et al., J. Phys. A. **9**, 1553 (1976) and Ref. 6.

[16] N. Prantzos and M. Casse, Astrophys. J. (Suppl.) **92**, 575 (1994), though, have suggested that perhaps cosmic ray fluxes in galaxies were much higher (by a factor 200-300) during a few 10^8 years of their early life and this bright phase enhanced their gamma ray emissivity and produced the presently observed GBR. This explanation seems ad hoc and relies on rather little observational evidence.

[17] S. van den Bergh, Astron. and Astrophys. **264**, 75 (1992).

[18] T.J. Ponman and D. Bertram, Nature **363** 51 (1993).

[19] U.G. Briel *et al.*, Astr. and Astrophys. **259**, L31 (1992).

[20] The gamma ray flux from the Small Magellanic Cloud (SMC) which was measured by EGRET was used by P. Sreekumar, *et al.*, Phys. Rev. Lett. **70**, 127 (1993) to argue that the high energy cosmic ray flux is not universal. However, the galactic magnetic field may shield the SMC from low energy cosmic rays. Moreover, the argument of Sreekumar *et al.* is limited only to electrons and low-energy nuclei with ($E << 10\ GeV$), as noted by A. Dar *et al.*, Phys. Rev. Lett. **71**, 3394 (1993).

[21] B.P. Houston et al., J. Phys. G **10**, L147 (1984), used the flux detected by COS-B gamma ray telescope from the direction of NGC 1275 in the Perseus cluster (see A. Strong and G.F. Bignami, Astrophys. J. **274**, 549 (1983)) to argue that cluster emission could explain the extragalactic GBR. However, the flux level detected by COS-B from Perseus was not confirmed by CGRO.

[22] A. Dar, Phys. Rev. Lett. **51**, 227 (1983); Technion Report PHYS-84-41 (unpublished).

[23] P. Lipari, Astroparticle Phys. **1**, 195 (1993).

[24] T.C. Weekes, ucl. Phys. B (Proc. Suppl.) **38**, 457 (1995).

[25] Y.C. Lin et al., Astrophys. J. **401**, L61 (1992).

[26] F.W. Stecker et al., Astrophys. J. **390**, L49 (1992).

[27] F. Halzen, Nucl. Phys. B (Proc. Suppl.) **38**, 472 (1995) and references therein.

[28] See for instance J. G. Learned, Nucl. Phys. B (Proc. Suppl.) **38**, 484 (1995) and references therein.

Figure Caption

FIGURES

Fig. 1. Comparison between the predicted NBR produced by blazars (dotted line), by a universal MW-like cosmic ray flux in groups and clusters (dashed line), by cosmic rays in the MW galaxy from the direction of the galactic center (dashed-doted line) and the predicted atmospheric neutrino background at 0^0 and 90^0 zenith angles (full lines).